N89-24723

A Three Solar Cell System Based on a Self-Supporting, Transparent AlGaAs Top Solar Cell*

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Abstract

Development of a three solar cell stack can lead to practical efficiencies greater than 30% (1×,AM0). A theoretical efficiency limitation of 43.7% at AM0 and one sun is predicted by our model. Including expected losses, a practical system efficiency of 36.8% is anticipated. These calculations are based on a 1.93eV/1.43eV/0.89eV energy band gap combination. AlGaAs/GaAs/GaInAsP materials can be used with a six-terminal wiring configuration. A current-matched, two-terminal wiring configuration yields a practical system efficiency of 34.2% (1×,AM0). This is based upon an optimum bandgap combination of 1.93eV/1.35eV/0.95eV, and corresponds to the same top and bottom materials and the substitution of InP for GaAs.

The key issues for multijunction solar cells are the top and middle solar cell performance and the sub-bandgap transparency. AstroPower has developed a technique to fabricate AlGaAs solar cells on rugged, self-supporting, transparent AlGaAs substrates. Top solar cell efficiencies greater that 11% AM0 have been achieved.

State-of-the-art GaAs or InP devices will be used for the middle solar cell.

GaInAsP will be used to fabricate the bottom solar cell. This material is lattice-matched to InP and offers a wide range of bandgaps for optimization of the three solar cell stack. LPE is being used to grow the quaternary material. Initial solar cells have shown open-circuit voltages of 462 mV for a bandgap of 0.92eV.

This paper will discuss design rules for the multijunction three solar cell stack and will present the progress in the development of the self-supporting AlGaAs top solar cell and the GaInAsP bottom solar cell.

Introduction

Multijunction solar cells, mechanically-stacked or monolithic, present a major improvement in power density in space. For a practical system, a mechanically-stacked tandem solar cell efficiency of over 30% is possible in the long term and greater than 25% for the short term [ref. 1]. One tandem approach uses the top solar cell to boost the performance of the lower bandgap solar cell. An

* The GaInAsP bottom solar cell work was supported in part by the Air Force Aero Propulsion Laboratory under contact No. F33615-88-C-2807.

alternative approach is based upon scavenging low energy photons from a good, relatively wide bandgap top solar cell [ref. 2]. Combining both tandem solar cell approaches naturally leads to a three solar cell stack with efficiencies of over 40% at AM0 and one sun insolation.

A six-terminal wiring configuration is being proposed for the three solar cell stack. A two terminal wiring configuration requires the stacked solar cells to be current matched. In a radiation orbit, where the radiation damage to the three solar cells will cause different degrees of damage, current-matched multibandgap solar cells are current limited by the solar cell generating the least current. This current mismatch will result in more power loss over the lifetime of the array when compared to the six-terminal wiring configuration.

The key to high efficiency mechanically-stacked multijunction solar cells is the top solar cell. This top solar cell must: i) be highly efficient since one-half of the stack efficiency is the result of the top solar cell, and ii) be highly transparent to sub-bandgap photons. In this paper, the design rules for the multijunction will be discussed, and the progress in the development of the top and bottom solar cell will be discussed.

Design

Originally, the theoretical limits for the three solar cell stack (TSCS) were determined using a solar cell model by Nell [ref. 3] based upon tabulated standard spectra and the fit of experimentally achieved open-circuit voltages assuming unit quantum efficiency. Nell's model predicts an efficiency limit of 41.5% at AM0 and one-sun insolation with a bandgap combination of 2.28eV, 1.55eV, and 0.99eV. However, these specific bandgap choices do not utilize existing, well-developed technologies. In addition, more recent work by Terranova and Barnett [ref. 4] indicate that Nell's model underestimates the open-circuit voltages.

The model being used to predict the solar cell performance is that of Nell, but modified by Terranova and Barnett. The model was modified by using fundamental parameters to estimate the open-circuit voltages of well known materials in accord with the diode equation. Using this approach, the open-circuit voltages predicted by the model agree very well with experimental results of well developed solar cells.

Due to material limitations, AstroPower proposes bandgap choices of 1.93eV, 1.43eV and 0.89eV for the TSCS wired in a six-terminal configuration. Our model predicts an efficiency limit of 43.7% AM0, 1×. At a concentration ratio of 100×, this bandgap combination yields a limit of 48.9%. The 100× values are obtained by assuming a 100× increase in short-circuit current values and scaling other values in accordance with the diode equation.

For a two-terminal wiring configuration, the requirement of current-matching changes the bandgaps of the middle and bottom solar cell. Using a 1.93eV, 1.35eV and a 0.95eV bandgap combination, the model predicts an efficiency limit of 40.7% at 1×, AM0. At 100× AM0, an efficiency limit of 45.1% exists. By manipulating the energy bandgaps in the TSCS, only a small penalty in efficiency exists when the requirement for current matching is imposed.

Table I illustrates the theoretical maximum efficiency predicted by the model.

The proposed bandgap combination for the six-terminal wiring configuration corresponds to an $Al_{0.37}Ga_{0.63}As$ top solar cell, a GaAs middle solar cell, and a GaInAsP bottom solar cell. For the two-terminal case, the top and bottom materials remain the same, and the GaAs middle solar cell is replaced with InP.

AlGaAs solar cells have demonstrated high efficiencies, and AlGaAs is the most developed material for a top solar cell [ref. 5]. AstroPower has developed a technique to fabricate AlGaAs solar cells on a transparent AlGaAs substrate. This approach utilizes the most developed wide bandgap material on a transparent substrate.

The middle solar cell in the TSCS is GaAs or InP depending on the wiring configuration. GaAs solar cells are approaching their practical efficiency limit; hence, they represent a mature technology in the TSCS. InP solar cells represent a newer technology; however, recent technological breakthroughs indicate an advanced stage for this material. Using either material for the middle solar cell will not limit the TSCS performance.

GaInAsP is the material of choice for the bottom solar cell. This quaternary material offers lattice-matched alloys to InP with a tunable bandgap range of 0.75eV to 1.35eV. This material has been successfully developed for device applications in the fiber-optic and semiconductor-laser fields. This wide technology base is directly applicable to material development for bottom solar cell designs.

Practical System Performance

The potential performance of a photovoltaic material can be predicted through the comparison of the modelled theoretical maximum performance versus the achieved performance of well developed solar cells. A survey of the literature indicates that, in general, well-developed solar cells achieve 96%, 91% and 96% of their theoretical limits for open-circuit voltage, short-circuit current and fill factor, respectively [ref. 2]. Using these "scale factors", one may predict the "best case" performance of a photovoltaic material including optical and electrical losses. Table II illustrates the "best case" performance of a GaAs solar cell compared to the best reported device in literature.

This approach of scaling theoretical limits to predict the "best case" performance has been demonstrated to be valid for all well-behaved solar cells. This is particularly true of the III-V compounds. Using this approach, we can predict the performance of the TSCS by scaling each solar cell from the model's theoretical limit to the "best case" performance.

Assuming 100% transmission of the photons less energetic than the bandgap, we may predict the performance of each individual solar cell. By reducing the current in the middle (bottom) solar cell by the current generated in the top (top two) solar cells, an evaluation of the stack can be done. This approach is valid since the model assumes unit quantum efficiency. When using existing devices in a stack, one should convolute the spectrum with the external quantum efficiency to determine the current generated in the middle and/or bottom solar cell(s). Using the "scale factors", and reducing the current to simulate the TSCS, the best case prediction is given is Table III.

In our preliminary study, our 4mm diameter devices (on 5mm × 5mm die) were limited by a shunt diode, hence the devices suffered from lower than expected fill factors as shown in Figure 3. The origin of the shunt diode has been determined, and future devices will reflect this improvement. Under concentrated light, this problem was eliminated. Using the concentration fill factor, an analysis of our device was done. This is illustrated in Table IV.

The use of the "concentration" fill factor is reasonable. Mayet [ref. 7] have fabricated 1.89eV solar cells from AlGaAs with fill factors of 0.874. The most needed improvement for our preliminary AlGaAs devices (other than FF) is in the open-circuit voltage. This will be accomplished by optimizing the junction fabrication technique and the precise control of the base layer doping.

The AlGaAs devices show good current collections. An external quantum efficiency curve is shown in Figure 4. The external quantum efficiency measurement indicates good blue response and good bandedge response. The good blue response indicates that the window layer is reducing surface recombination. The good bandedge response indicates that the diffusion length is not limiting device performance.

GaInAsP Bottom Solar Cell Development

GaInAsP is the material system of choice for the bottom solar cell. This system offers a tunable bandgap range (0.35 to 2.26eV) low enough for bottom cell requirements with compositions lattice-matched to InP for bandgaps between 0.75 and 1.35eV. GaInAsP material technology has been successfully developed for device applications in the fiber-optic and semiconductor-laser field. This wide technology base is directly applicable to material development for bottom solar cell designs.

AstroPower is using liquid phase epitaxy (LPE) to develop GaInAsP devices down to 0.89eV. Smooth surface morphology has been obtained for bandgaps down to 0.92eV using modified meltback and two-phase solution techniques. Figure 5 is a photograph of this smooth morphology. Figure 6 is a EDS quantitative profile, showing layer composition and thickness.

Homojunction 0.92eV GaInAsP solar cells have been fabricated in our laboratory. Undoped 0.92eV GaInAsP material was diffused with zinc; device areas were chemically isolated; and Au alloy contacts were applied. Emitter thickness and grid design have not yet been optimized. Open-circuit voltage values up to 462mV at AM0 (1×) were recorded. This corresponds to 78% of the theoretical maximum open circuit voltage value calculated for 0.92eV material.

These results are particularly encouraging considering that open-circuit voltage values are a good indicator of the performance potential of solar cell materials, like silicon and GaAs [ref. 2]. In addition, the open circuit voltage exceeds that of well-developed germanium bottom solar cells by 44%. Recently reported values for germanium bottom solar cells are 306mV at AM1.5 (238×) or 320mV at AM0 (1×) [ref. 8].

Figure 7 shows a quantum efficiency versus wavelength plot for the 0.92eV bottom solar cell covered by an InP filter.

The "peaked" response in the quantum efficiency is the result of an unoptimized junction. The junction on this device was too deep and surface recombination dominated the high energy

Device Fabrication

The AlGaAs top solar cell and the GaInAsP bottom solar cell are being developed in our laboratories. The material is being grown by liquid phase epitaxy (LPE). LPE is the technique of choice given the stoichiometry control, the tendency of the impurities to segregate away from the solid, and the longer diffusion lengths. LPE is known to produce devices that are superior in performance to those grown by other methods. The majority of the commercial III-V semiconductor devices being produced in Japan are grown by LPE.

AlGaAs Top Solar Cell Development

AlGaAs solar cells have demonstrated high efficiencies, and AlGaAs is the most developed material for a top solar cell [ref. 5]. However, all AlGaAs solar cells reported in the literature are fabricated on GaAs substrates. This opaque substrate must be removed before application to a mechanical stack. Integrating a highly transparent, self-supporting AlGaAs top solar cell coupled with existing, well-developed solar cells will achieve increases in solar cell efficiency with multijunction structures. A technique to fabricate AlGaAs solar cells on transparent AlGaAs substrates has been developed. AstroPowers' approach utilizes the most developed wide bandgap material on a transparent substrate.

The rugged, self-supporting, transparent AlGaAs top solar cell can be mechanically stacked on any well developed, existing solar cell. The key issue for multijunction solar cells - - mechanically stacked or monolithic - - is the top solar cell. This solar cell must be transparent to the sub-bandgap photons, and must be approaching its theoretical efficiency limit. It is our practice to first investigate the material transparency since this is the most critical parameter. Figure 1 shows quantum efficiency curves for a silicon solar cell with and without an AlGaAs filter. This AlGaAs filter was transparent to 91% of the photons less energetic than the bandgap of the active device layer.

To improve the transparency, one must determine where the losses have occurred. Two possible loss mechanisms exist: i) reflection, and ii) free carrier absorption. Each loss mechanism can be reduced through optical optimization. More detailed measurements on our AlGaAs filter, reflection + transmission (R+T), indicate that the effect of free-carrier absorption is less than 2%. Sub-bandgap transparency is not a problem with this material.

AstroPower's preliminary work on this system has yielded a 11.2% (AM0, 1×) AlGaAs top solar cell. The detailed characteristics were V_{oc}=1.285 volts, J_{sc}=15.7 mA/cm^2 , and FF=0.75. In addition, we have demonstrated transparency greater than 90%. Our preliminary investigation indicates the lattice-matched AlGaAs system is easier to work with and, hence, will yield faster results.

AstroPower recently investigated 1.93eV AlGaAs solar cells. We have demonstrated the capability of growing transparent AlGaAs substrates, and the capability of fabricating AlGaAs solar cells. Our best one sun (AM0) device is 11.2% efficient. These devices are shown in Figure 2. response. Nonetheless, the sub-bandgap transparency of the filter is encouraging as is the response of the GaInAsP in the "stacked" situation.

Conclusion

Solar cell efficiencies greater than 30% AM0 are realizable in the near future with a three solar cell stack (TSCS). With expected losses, a practical system efficiency of 36.8% is anticipated. These calculations are based on the 1.93eV/1.43eV/0.89eV energy bandgap combination. AlGaAs/GaAs/GaInAsP materials can be used with a six-terminal wiring configuration. A current-matched, two-terminal wiring configuration yields a practical system efficiency of 34.2% (1×,AM0). This is based upon an optimum bandgap combination of 1.93eV/1.35eV/0.95eV, and corresponds to the same top and bottom materials and the substitution of InP for GaAs.

The self-supporting AlGaAs structure eliminates the low yield problem that others encountered when trying to remove the fragile AlGaAs from the GaAs substrate. Technological risk is minimized for all materials by drawing upon available technology. The key to high efficiency triple stacks is in the top and middle solar cell. Both must be approaching their efficiency limit and must be highly transparent to photons less energetic than their bandgaps.

Continued progress for the AlGaAs top solar cell and the GaInAsP bottom solar cell will result in practical system efficiencies greater than 30% AM0.

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TABLE I

Predicted Theoretical Maximum Efficiency
for the Six-Terminal and Two-terminal
Three Solar Cell Stack, AM0

6-TERMINAL CONFIGURATION

Bandgap (eV)	Voc (volts)	Jsc (mA/cm^2)	FF	Eff [1x] (%)	Eff [100x] (%)
1.93	1.58	21.8	0.91	23.2	25.0
1.43	1.07	16.7	0.88	11.6	13.0
0.89	0.54	27.9	0.80	8.9	10.9
		Stack Efficiency		43.7	48.9

2-TERMINAL CONFIGURATION

1.93	1.58	19.7	0.91	20.9	22.5
1.35	0.99	19.7	0.87	12.7	14.1
0.95	0.60	19.7	0.81	7.1	8.5
		Stack Efficiency		40.7	45.1

TABLE II

Expectation of "Best Case" GaAs Solar (AMO)

	Voc (volts)	Jsc (mA/cm2)	FF	Eff (%)
Theoretical	1.09	38.5	.88	27.3
%Theoretical	96%	91%	96%	
Best Case	1.05	35.0	.84	22.9
Best Achieved [6]	1.06	32.4	.85	21.5

TABLE III

Best Case Prediction at AMO
For The Three Solar Cell Stack

6-TERMINAL CONFIGURATION

Material	Voc (volts)	Jsc (mA/cm^2)	FF	Eff(1x) (%)	Eff(100x) (%)
AlGaAs	1.52	19.8	0.88	19.5	21.0
GaAs	1.03	15.2	0.85	9.8	10.9
GaInAsP	0.52	25.4	0.77	7.5	9.1
		Stack Efficiency		36.8	41.0

2-TERMINAL CONFIGURATION

AlGaAs	1.52	17.9	0.88	17.7	19.0
InP	0.96	17.9	0.84	10.6	5.9
GaInAsP	0.57	17.9	0.78	5.9	7.1
		Stack Efficiency		34.2	38.0

TABLE IV

Potential of 1.93eV AlGaAs Solar
Cells Using "Best Case" Fill Factor

Concentration	Voc (volts)	Jsc (mA/cm2)	FF	Eff (%)
1x	1.285	15.4	.88	12.9
25x	1.38	385.0	.88	13.8
100x	1.42	1540.0	.88	14.2

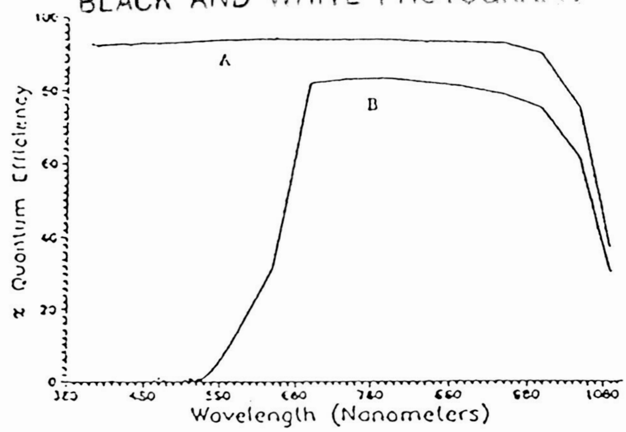

Figure 1. A) Q.E. of Silicon Solar Cell without AlGaAs filter.
B) Q.E. of Silicon Solar Cell with AlGaAs filter.

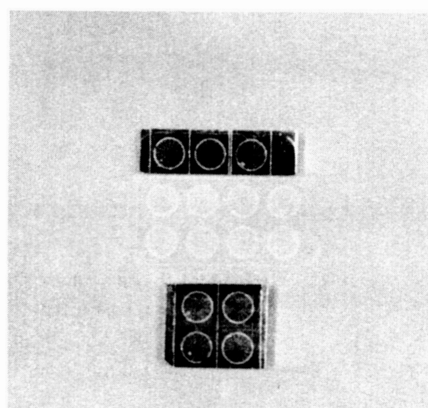

Figure 2. AlGaAs Devices with Concentrator Mask.

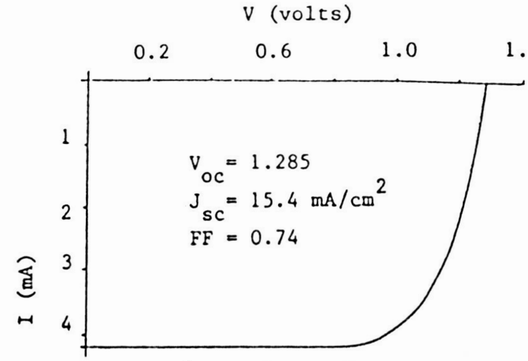

Figure 3. Representative I-V Curve for an AlGaAs top solar cell at 1X, AM0.

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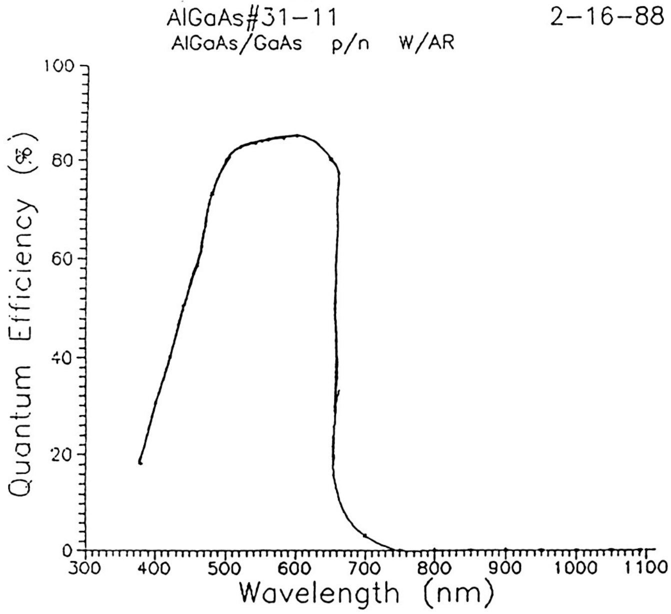

Figure 4. Representative External Quantum Efficiency Plot of an AlGaAs Top Solar Cell.

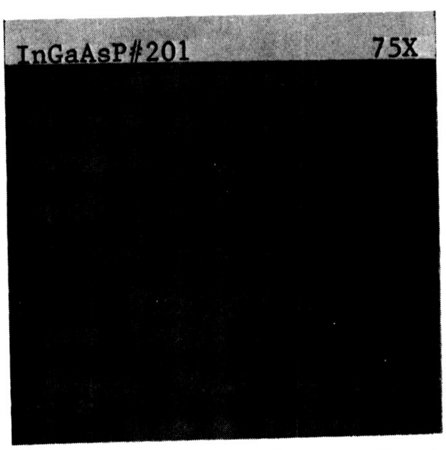

Figure 5. Smooth, unfeatured surface morphology of 0.92eV GaInAsP grown by LPE.

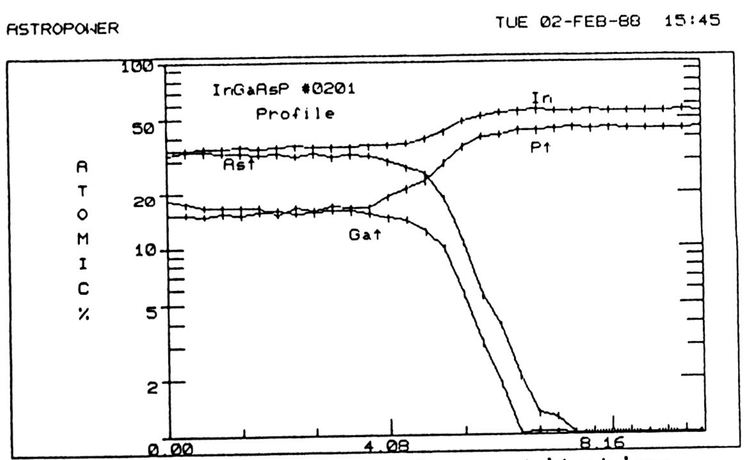

Figure 6. EDS quantitative profile of 0.92eV GaInAsP composition.

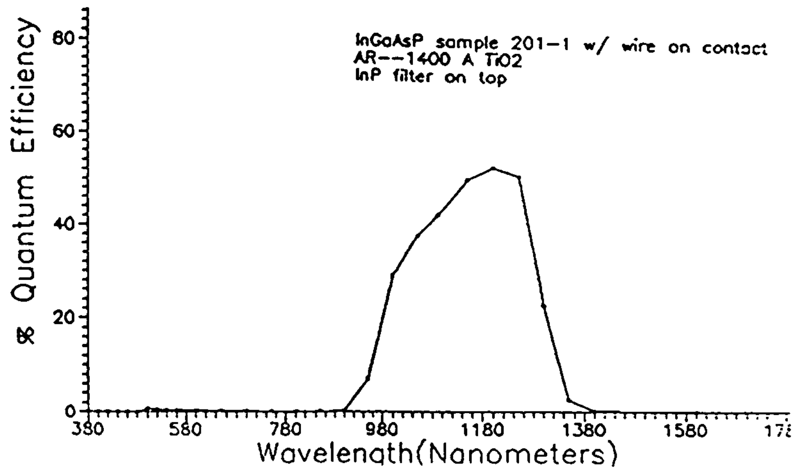

Figure 7. Quantum efficiency of 0.92eV GaInAsP solar cell under an InP filter.